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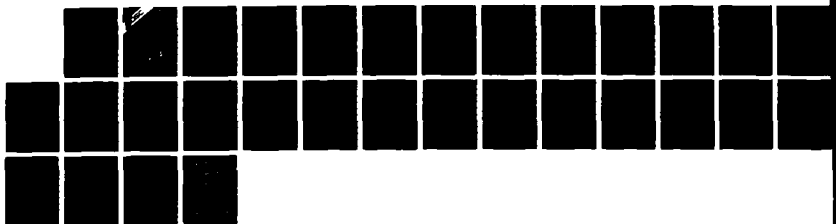
104-KM UNREPEATED BIDIRECTIONAL FIBER OPTIC
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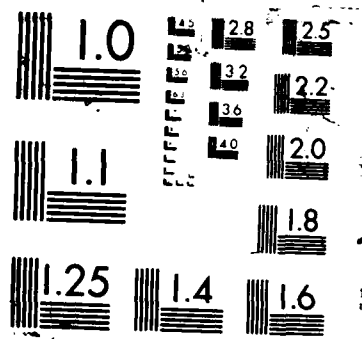
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Technical Report 1185
May 1987

104-km Unrepeated Bidirectional Fiber Optic Demonstration Link

M. R. Brininstool



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ADMINISTRATIVE INFORMATION

This report documents work performed during FY 86 on an unrepeated 104-km bidirectional single-mode fiber optic demonstration link. This work was funded by the Office of Naval Research, Code 01123, under program element N0001487AF0001, project number CG92. The goal of the project was to demonstrate full-duplex transmission of command-control and television data over 100 km of optical fiber by means of commercially available components and with no optical repeaters.

Released by
S.J. Cowen, Head
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Under authority of
A.J. Schlosser, Head
Ocean Engineering
Division

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CONTENTS

	<u>Page</u>
1.0 INTRODUCTION	1
2.0 SYSTEM DESCRIPTION	2
2.1 1.3- μ m Low-Data-Rate Downlink	3
2.2 1.55- μ m High-Data-Rate Uplink	4
3.0 SYSTEM COMPONENTS	4
3.1 Laser Diode Transmitters	4
3.2 Photodiode Detectors/Preamplifiers	6
3.3 Single-Mode Optical Fiber/Cable	6
3.4 Wavelength-Division Multiplexers	9
3.5 Variable Optical Attenuator	12
4.0 FOLLOW-ON DEMONSTRATIONS	13
4.1 Present 1.3- μ m Link Capacity	13
4.2 Areas of Improvement for 1.3- μ m Link	14
4.3 Projected 1.3- μ m Link Capacity	15
4.4 Present and Projected 1.55- μ m Link Capacity	16
5.0 CONCLUSIONS	17
6.0 REFERENCES	18
Appendix A: Component Manufacturer List	19
Appendix B: Equipment List	21
Appendix C: Physical Dimensions of Components	23
Appendix D: Electrical Power Consumption of Components	24



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ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1. Spectral attenuation of optical fibers	2
2. 100-km, bidirectional single-mode fiber optic system	3
3. Functional schematic of laser transmitter	5
4. PINFET pin assignments	7
5. PINFET circuit schematic	7
6. Optical fiber/cable splice topology	9
7. Bulk optic single-mode WDM design	10
8. Filter transmission curves for single-mode fiber WDM	10
9. BER vs. electrical SNR	11
10. Diagram of optical system with attenuator	13

TABLES

<u>Table</u>	
1. Laser transmitter specifications	5
2. PINFET performance values	8
3. Optical fiber data	8
4. System link loss budget	11
5. WDM manufacturer's specifications and measured values	12
6. Present maximum system length at 1.3 μm	14
7. Projected system length at 1.3 μm	15
8. Present 1.55- μm loss budget	16

1.0 INTRODUCTION

The objective of this project is to demonstrate that bidirectional data can be transmitted over 100 km of optical fiber without the use of optical repeaters and employing only state-of-the-art, commercially available components. These were the only design constraints. No exotic transmitters or super-cooled detectors could be used. Commercially available optical fiber incorporated into an actual cable was employed.

Unlike so-called "champion demonstrations," in which distance records are set periodically and reported in the literature, the subject demonstration relates more closely to achievable system performance available with off-the-shelf components. The following differences exist:

1. Commercial laser diodes incorporated into electronic transmitters were used rather than experimental lasers monitored by technicians and optimized manually.
2. All components are available off-the-shelf and, in the case of the optical fiber, incorporated into an actual cable.
3. A modest operational safety factor (5 dB, minimum) is incorporated into the system versus the unity (0 dB) system safety factor associated with a champion demonstration.
4. The data link is bidirectional, using wavelength duplexing, not simplex, to better simulate operation in a long-haul duplex communications link.

Television data are transmitted uplink, and computer control data are sent downlink. The TV composite is modulated using a pulse-frequency modulation (PFM) encoding scheme with a center frequency of 14.3 MHz, and the control data rate is Manchester encoded at 19.2 kbps. The link is operated full duplex.

To achieve long, unrepeated transmission lengths, state-of-the-art lasers, wavelength-division multiplexers (WDMs), fibers, and receivers are employed. Minimization of the fiber attenuation is critical. Figure 1 illustrates typical spectral attenuation curves for optical fibers. The strong dependence of optical attenuation on wavelength is due to Rayleigh scattering in the glass. Attenuation generally decreases at longer wavelengths. Therefore, the first step in extending system length is to use optical emitters at longer wavelengths, thereby utilizing the lower fiber attenuation. Two minimum-attenuation windows exist, at 1.3 μm and 1.55 μm . Instead of LEDs, laser diode transmitters operating at these windows are used because of their high output power levels. Typical LED transmitters emit 10 μW peak power (-20 dBm) from a single-mode fiber pigtail, while lasers emit typically 1 mW peak power (0 dBm). Lasers also have much narrower spectral emission widths, 2-4 nm, compared to 50-100 nm FWHM (full width, half-maximum) for LEDs. This narrow spectral width limits material dispersion in the fiber, leading to higher bandwidth capacities.

The curve labeled "Multimode 1980" in Figure 1 shows attenuation levels for a multimode graded-index fiber. The lower curve, labeled "Single Mode 1982," is spectral attenuation for a single-mode optical fiber. Note the improved transmissivity at 1.3 μm and 1.55 μm . Using single-mode fiber is the second step in maximizing the system length. In addition to lower attenuation, single-mode fiber has no modal dispersion and

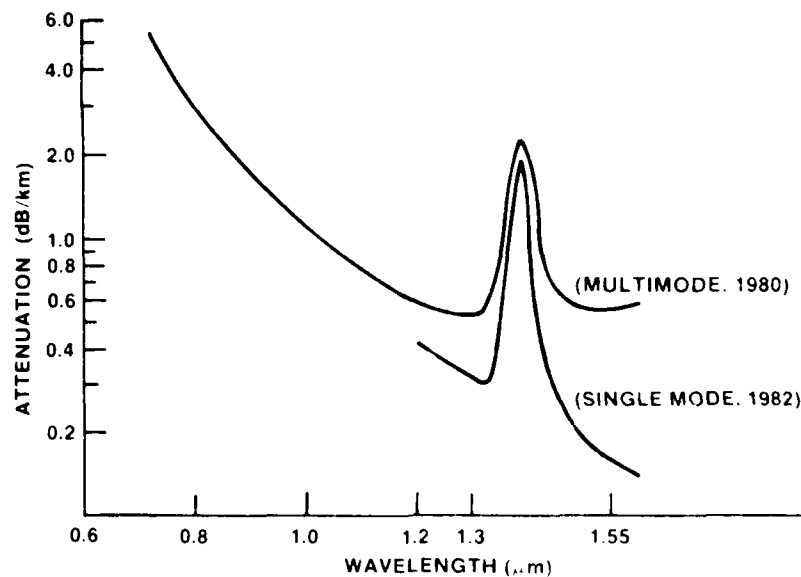


Figure 1. Spectral attenuation of optical fibers (from Reference 1).

thus has significantly higher bandwidth capacity. A typical bandwidth-length product for multimode fiber is 400 Mbps-km, while for single-mode fiber this product is 45 Gbps-km. This becomes critical at longer system lengths in order to avoid pulse-dispersion problems.

At 1.3 μm and 1.55 μm , a unity gain ternary type InGaAs photodetector is used. The photodetector is coupled to an FET preamplifier in a design which is tailored to provide the maximum sensitivity at the applicable data rate.

Increased source output power levels, reduced fiber attenuation, improved bandwidth-length product, and maximized receiver sensitivity are all key areas of improvement. When combined with low-loss fiber splices and efficient WDMs, unrepeated system lengths greater than 100 km are readily attainable.

2.0 SYSTEM DESCRIPTION

An electro-optical system diagram is shown in Figure 2. This illustrates the major components of the demonstration system, excluding the optical cable. Several factors dictate that the low-data-rate link operate at 1.3 μm and the high-data-rate link at 1.55 μm . Receiver sensitivity level is approximately proportional to the square root of the bandwidth, so the sensitivity of the low-data-rate receiver is considerably better than that of the high-data-rate receiver. Optical fiber attenuation is inversely proportional to the fourth power of the source emission wavelength. Attenuation at 1.55 μm is significantly lower than attenuation at 1.3 μm . The additional fiber losses at 1.3 μm are therefore compensated for by having a high receiver sensitivity. For the low-data-rate downlink, an ordinary computer terminal is used to send commands to a receive terminal via the 1.3- μm fiber optic link. A television camera transmits high-data-rate video

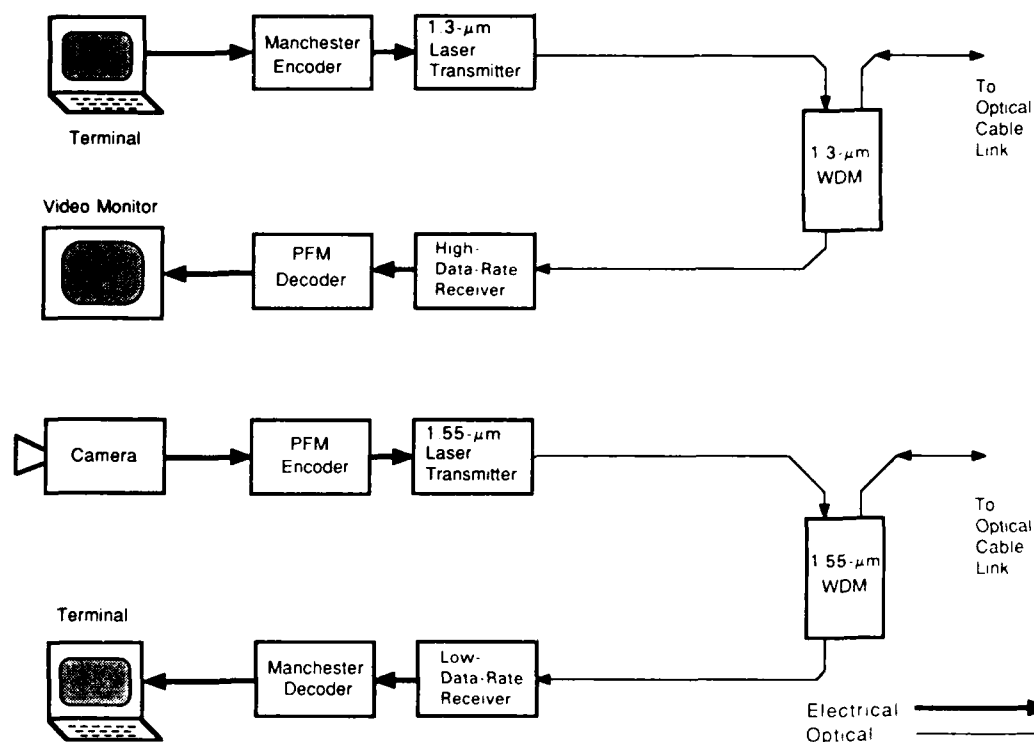


Figure 2. 100-km, bidirectional single-mode fiber optic system.

image data to a monitor via the 1.55- μm uplink. Each link is described in the following paragraphs.

2.1 1.3- μm LOW-DATA-RATE DOWNLINK

For the 1.3- μm low-data-rate downlink portion of the demonstration, two smart computer terminals are used to generate and receive digital data. Text is typed on to the transmit terminal screen. A "send" command then transfers the data via the fiber optic link to the receive terminal, where it is displayed. The 19.2-kbps asynchronous output data from the transmit terminal are Manchester encoded. Manchester encoding offers many advantages over conventional NRZ (non-return to zero) formats (References 2, 3). A Manchester code is a transitional rather than a state code. A rising edge represents a zero and a falling edge represents a one. Transitions occur in every bit period, so the signal forms its own clock. Therefore only one line is needed to carry both data and clock information. Manchester code eliminates DC and low-frequency data. The code has its own error-detection capability because a bit always has a level transition in the middle of the cell. Therefore, any inversions in either cell half caused by noise can be detected. From the Manchester encoder, the data are shifted to an ECL voltage level and then applied to the input of the 1.3- μm laser diode transmitter. Here the electrical data are converted to optical pulses. These pulses are transmitted via a fiber optic pigtail into the wavelength-division multiplexer, which in turn injects the data stream into the transmission line fiber. At the receiver end, the demultiplexer extracts the data and directs it, via a multimode fiber pigtail, to the receiver. The PINFET receiver converts the optical signal back to electrical levels. The output from the PINFET is buffered and fed to the Manchester decoder circuitry, which reconstructs the original signal and sends it to the receiver terminal for display.

2.2 1.55- μm HIGH DATA-RATE UPLINK

The uplink data consist of a PFM-encoded video signal transmitted over the fiber at 1.55 μm . A video camera outputs a 4.5-MHz composite video signal and sends it to a PFM encoder. PFM encoding is a version of FM in which pulses are transmitted at the zero-crossings of the FM signal. Essentially, video signal amplitudes are mapped into relative time differences between pulses (Reference 4). PFM offers both simplicity and excellent spread-spectrum processing gain. Since pre-emphasis and de-emphasis networks are used, substantially improved SNRs are obtainable upon demodulation. PFM encoding permits a designer to take full advantage of a fiber's available bandwidth-length product. Because the pulse duty factor is much less than the 50 percent common in digital systems (15 percent in this case), the potential exists to operate the laser transmitter at higher peak output levels without exceeding the average power specification. This advantage is currently not exploited, however, because it is not the video channel, but rather the digital data channel, which limits the maximum attainable link length in this demonstration.

The output of the PFM circuitry is used to drive the 1.55- μm laser transmitter. Optical injection, transmission, and extraction is similar to the 1.3- μm link, and the 1.55- μm receiver transfers the data to the PFM demodulator. The resulting video signal is displayed on a monitor.

3.0 SYSTEM COMPONENTS

The following sections describe the optical system components in more detail. A component manufacturer list is provided in Appendix A. The list shows the winning bid as the first source for each component and includes the prices. Other bidding manufacturers are listed below them. Appendix B provides a list of other equipment used for the demonstration. These lists do not represent any endorsement of the manufacturers or their distributors. Appendix C gives the physical dimensions for most of the components and circuits employed for the demonstration. Appendix D tabulates the electrical power consumption of the components.

3.1 LASER DIODE TRANSMITTERS

Laser diode transmitters are used to convert electrical data into optical signals. A laser is preferred over an LED for long-distance applications for several reasons: It has high output power; the narrow spatial emission pattern makes it compatible for efficient coupling to single-mode fibers; the narrow spectral linewidth minimizes material dispersion in the fiber; and rise times of lasers are an order of magnitude faster than those of LEDs.

Two single-mode laser transmitters are used in this system. One operates at a center wavelength of 1.3 μm and the other at 1.55 μm . Table 1 gives the manufacturer's data for the two transmitters.

Table 1. Laser transmitter specifications.

Manufacturer: PlessCor Optronics, Inc.

Laser Model:	<u>DTX-13-50</u>	<u>DTX-15-50</u>
	1.3 μm	1.55 μm
Peak Output Power from a 10- μm core pigtail	+2.4 dBm	-0.5 dBm
Center Wavelength	1.280 μm	1.544 μm
Spectral Width (FWHM)	1.2 nm	1.2 nm
Rise/Fall Time	1/1 ns	0.8/1.2 ns
Supply Current	550 mA	670 mA
Laser Bias Current	47 mA	44 mA
Supply Voltage	-5.2 V	-5.2 V

Figure 3 is a functional schematic of the laser transmitter. Each transmitter employs identical circuitry (Reference 5). The major components of the transmitter are the InGaAsP laser diode with optical fiber pigtail, laser driver circuitry, a thermoelectric cooler (TEC) control circuit, a power monitor feedback control circuit, and alarm

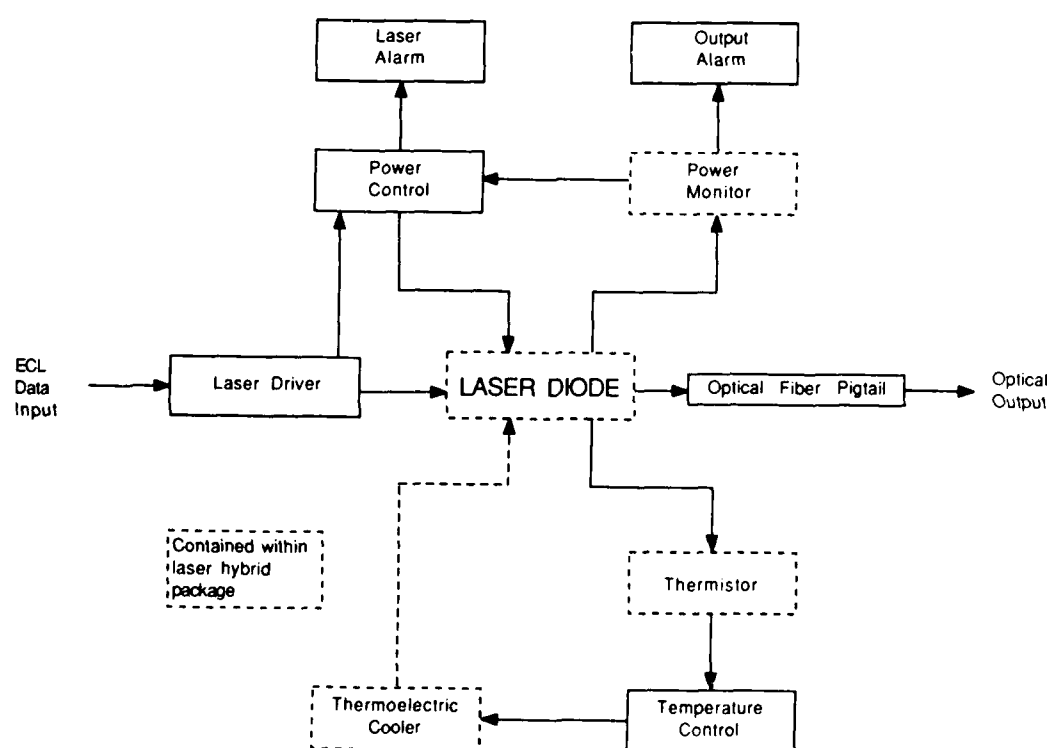


Figure 3. Functional schematic of laser transmitter (from Reference 6).

circuitry. One meter of a single-mode optical fiber pigtail is positioned in the beam from the laser diode in a manner which produces maximum coupling efficiency. The laser driver maintains the proper bias current and applies the ECL data input modulation current to the diode.

An optical power monitor photodiode is attached to the rear facet of the laser diode. This photodiode monitors emissions from the partially reflective rear-facet mirror of the laser. The detected current from the monitor diode closes an optical feedback control loop, which serves to maintain the bias current at a constant level regardless of aging and other perturbations.

Adjacent to the laser diode is a precision thermistor. This sensor measures the laser temperature and alerts the temperature control circuit of any deviations. The TEC is activated when the laser temperature exceeds 25 °C and quickly lowers the temperature back to normal. The laser diode, photodiode monitor, thermistor, and TEC are all housed within the laser hybrid 14-pin DIP. Alarm outputs are provided which alert the user when the bias current and optical output power exceed maximum levels.

3.2 PHOTODIODE DETECTORS/PREAMPLIFIERS

Detection of the optical data signals is achieved using pigtailed PINFET receiver modules (Reference 7). An InGaAs ternary detector, with a spectral response range of 1.0 μm to 1.65 μm , is coupled to a low-noise GaAs FET transimpedance amplifier in a hybrid circuit mounted in a standard 14-pin DIP. The feedback resistor is optimized for each received data rate used in the demonstration. Efficient coupling of incoming light to the detector surface is achieved using a multimode graded-index fiber pigtail with a 50- μm core diameter and an NA = 0.20. Figure 4 gives the DIP pin-out for the devices, and Figure 5 shows the PINFET circuit schematic. Table 2 lists performance values of each PINFET as measured by the manufacturer into a 1-k Ω load.

3.3 SINGLE-MODE OPTICAL FIBER/CABLE

The fiber used to achieve the 100-km demonstration milestone is a single-mode, dispersion-shifted fiber. The wavelength of zero dispersion, usually at 1.3 μm for doped silica, is shifted to the minimum-attenuation wavelength of 1.55 μm by grading of the core-cladding refractive index profile. Optical and physical characteristics of the fiber are given in the Table 3.

Unspliced fiber lengths of 100 km are currently unobtainable commercially; therefore, the 104-km length was constructed by fusion-splicing ten fiber segments. Each segment is 10.4 km long. The segments were packaged in a ten-element cable structure. The cable contains ten dielectric loose-tube units, each holding one fiber. The units are arranged circumferentially around a dielectric central strength member. The loose-tube arrangement is commonly employed in TELCOM cables and insures minimization of microbending attenuation due to spooling tension. The cable was shipped on a 2.2-m-diameter shipping spool and stored next to Building 53, Bayside, NOSC. Each end of the cable was fed into the building to a fusion-welding station, where the individual fibers were fusion-spliced and reinforced. Figure 6 depicts the cable-splice topology. Also shown are the measured attenuation values at 1.3 μm and 1.55 μm , and the splice losses at 1.55 μm .

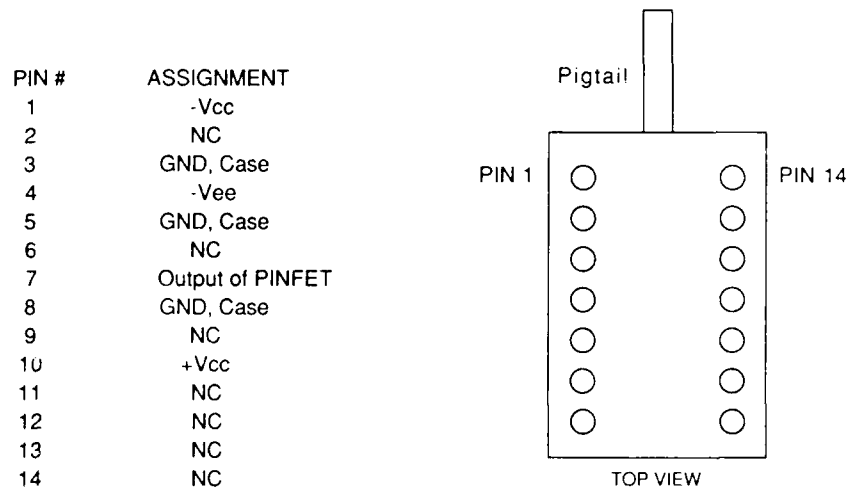


Figure 4. PINFET pin assignments (from Reference 8).

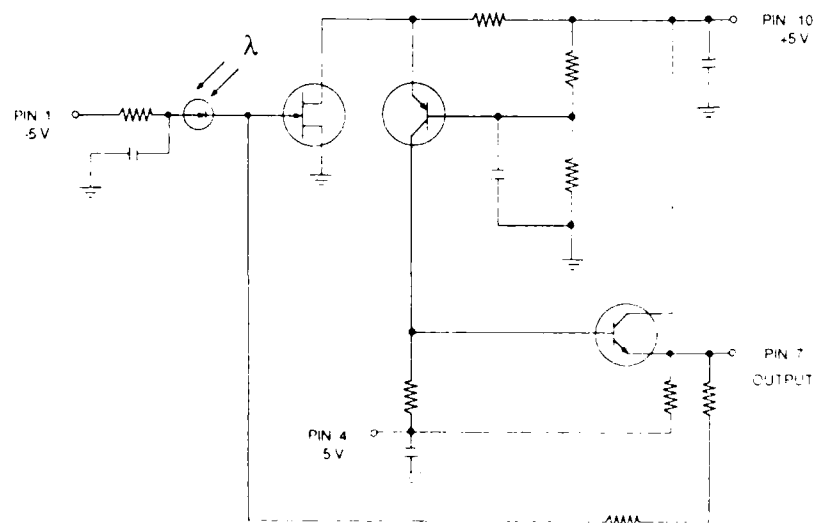


Figure 5. PINFET circuit schematic (from Reference 8).

Table 2. PINFET performance values.

Manufacturer: General Optronics

Model: GO PINFET

PINFET Wavelength:	1.3 μm	1.55 μm
Bandwidth (MHz)	0.8	50
Responsivity (A/W)	0.6	0.85
Noise Voltage (mV)	0.2	0.45
Transimpedance ($k\Omega$)	3,300	130
Dark Current (nA)	18	1
Average Sensitivity (dBm)	-62	-46

Table 3. Optical fiber data.

Manufacturer: Corning Glass Works

Model: SM/DSF Single-Mode, Dispersion-Shifted Fiber

Optical Characteristics:	Specified	Measured Average
Attenuation at 1550 nm	0.25 dB/km	0.212
at 1300 nm	0.45 dB/km	0.384
Cutoff Wavelength	1130 - 1270 nm	
Dispersion	2.5 ps/nm-km max at 1525 - 1575 nm	
Mode Field Diameter	9 μm typical	
Effective Core Refractive Index	1.476	
Physical Characteristics:		
Cladding Diameter	125 +/- 3 μm	
CPC Coating (UV Acrylate)	250 +/- 15 μm	
Proof Stress	0.35 GPa (50,000 psi)	
Length of Segment	10.4 km	

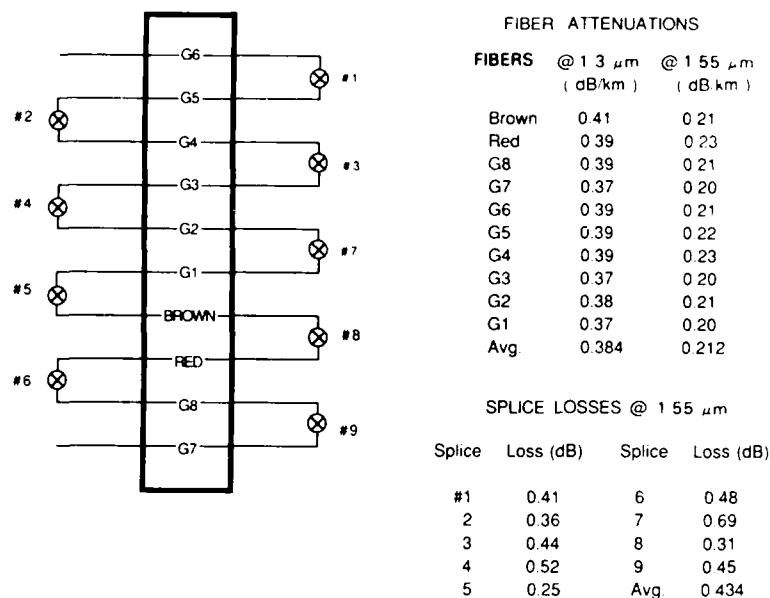


Figure 6. Optical fiber/cable splice topology.

3.4 WAVELENGTH-DIVISION MULTIPLEXERS

Bidirectional data transmission requires multiplexers to inject, extract, and isolate outgoing and incoming data streams over a single optical fiber (Reference 9). Significant optical isolation is required to prevent crosstalk between the local transmitter and local receiver. A pair of complementary wavelength-division multiplexers/demultiplexers (WDMs) are used. One multiplexer, a 1.3- μm WDM, injects outgoing light from the 1.3- μm laser diode transmitter into the transmission line and extracts incoming light from the distant 1.55- μm laser transmitter, directing it to the 1.55- μm receiver. The second multiplexer, a 1.55- μm WDM, performs a complementary function at the other end of the link.

Optical injection, extraction and isolation is achieved using a bulk optic design constructed with Selfoc lenses and cascaded dichroic filters. Figure 7 illustrates the technique. Bandpass dichroic filters are sandwiched between two 1/4-pitch Selfoc lenses. Single-mode-fiber transmitter and line ports and a multimode-fiber receiver port are attached to the Selfoc lens end faces. Light from the local transmitter is injected into the Selfoc lens, reflects off of the first dichroic filter, and is transferred into the line port. Incoming light from the line port passes through the cascaded dichroic filters and is directed to the local receiver. Isolation between the local transmitter and local receiver is accomplished in two ways. The dichroic filters reflect light from the local transmitter and pass light from the distant transmitter. The bandpass transmission curves for a set of filters are shown in Figure 8. In addition to filter rejection, any low-level light from the local transmitter that passes through the filters is directed to a point in the Selfoc lens opposite the receiver port, thereby providing additional isolation (approximately 30 dB) by directional coupling.

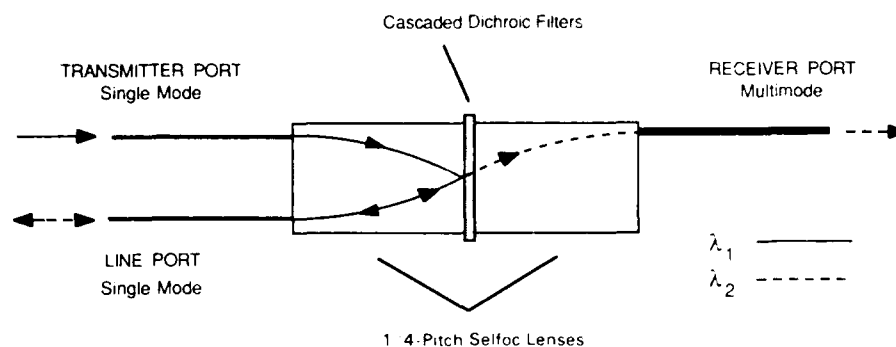


Figure 7. Bulk optic single-mode WDM design.

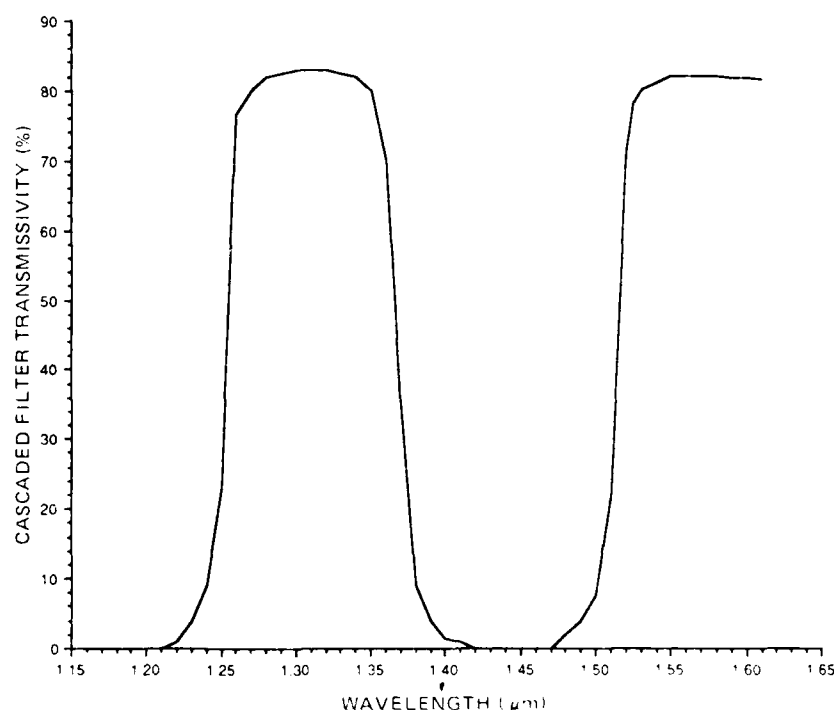


Figure 8. Filter transmission curves for single-mode fiber WDM (from Reference 10).

An analysis of the optical system loss budget for a 100-km link reveals the minimum WDM requirements. The first requirement is to determine the minimum allowable crosstalk level at the local receiver between the local transmitter power, the noise source, and the distant transmitted power—the signal. Referring to Figure 9, in order for a digital system to maintain a bit error rate (BER) of 10^{-9} , the electrical SNR must be at least 21.5 dB. The equivalent optical power SNR is half this, or roughly 11 dB minimum. In general, the local transmitter power level must be at least 11 dB lower at the receiver port than the received incoming signal power level in order to prevent interference. A budget is generated which estimates optical losses experienced by the signal as it passes through the system. To estimate the WDM isolation requirement, the dichroic filter losses are not included in the budget and the corresponding SNR is found. Table 4 shows the budget based on specified component performances.

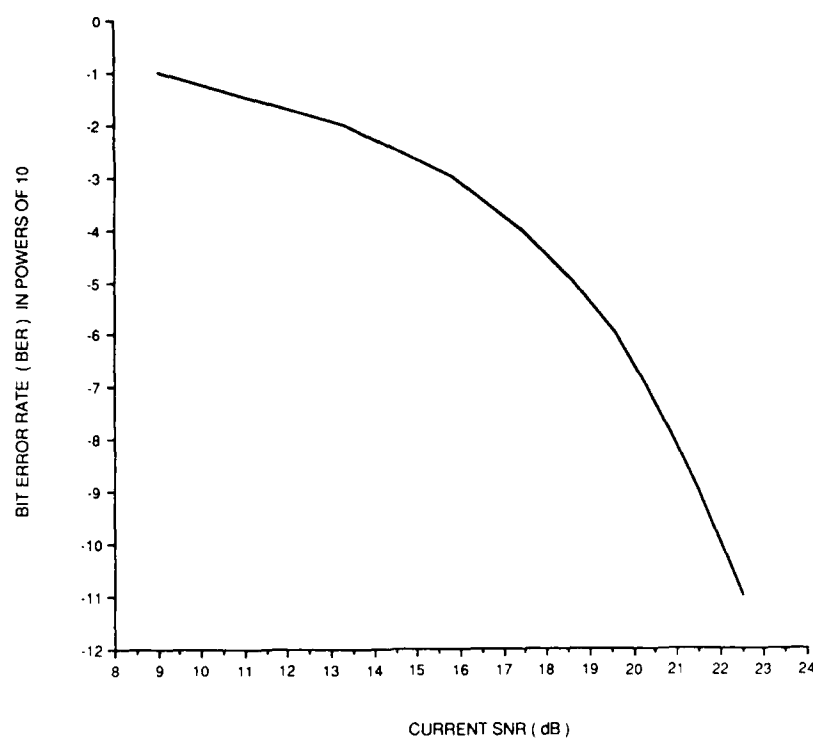


Figure 9. BER vs. electrical SNR (from Reference 11).

Table 4. System link-loss budget.

<u>Component Losses</u>	<u>Operation Wavelength</u>	
	<u>1.3 μm</u>	<u>1.55 μm</u>
XMIT-to-WDM Splice Loss	0.2 dB	0.2 dB
WDM Insertion Loss (T to L)	1.0	1.0
100-km Fiber Loss	45.0	25.0
Cable Splice Losses (11 splices)	2.2	2.2
WDM Insertion Loss (L to R)	1.5	1.5
WDM-to-Receiver Splice Loss	<u>0.2</u>	<u>0.2</u>
TOTAL LOSSES	50.1 dB	30.1 dB

The budget shows that for 100 km of fiber, the 1.3- μm link losses would be approximately 50 dB and the 1.55- μm link losses 30 dB. If equal power transmitters are assumed, then with no dichroic filters and neglecting isolation provided by directional coupling, the 1.3- μm receiver would have an SNR of -50 dB, and the 1.55- μm receiver

SNR would be -30 dB (note that these are negative numbers, which define an SNR which is much less than unity). Since a minimum SNR of +11 dB is required, the 1.3- μm WDM needs to provide 41 dB of isolation, and the 1.55- μm WDM needs at least 61 dB. A safety margin of 5 dB is added to allow for unknown factors. This brings the minimum isolation values to 46 dB and 66 dB, respectively.

The manufacturer's specifications and measured values for the WDMs delivered for the 100-km system are shown in Table 5.

Table 5. WDM manufacturer's specifications and measured values.

Manufacturer: JDS Optronics, Inc.

1.3- μm MUX/1.55- μm DEMUX, Model WD1315SB/1.5D

	Specification	Measured
MUX Channel Band	1.26 - 1.35 μm	1.27 - 1.34 μm
DEMUX Channel Band	1.525 - 1.60 μm	1.525 - 1.60 μm
Loss: MUX Channel	Less than 1 dB	0.5 dB
DEMUX Channel	Less than 1 dB	0.7 dB
Isolation	Greater than 46 dB	Greater Than 95 dB

1.55- μm MUX/1.3- μm DEMUX, Model WD1315SB/1.3D

MUX Channel Band	1.525 - 1.60 μm	1.525 - 1.60 μm
DEMUX Channel Band	1.26 - 1.35 μm	1.27 - 1.34 μm
Loss: MUX Channel	Less than 1.5 dB	0.6 dB
DEMUX Channel	Less than 1.0 dB	0.7 dB
Isolation	Greater than 66 dB	Greater than 69 dB

It is noted that the 1.55- μm MUX isolation measured by the manufacturer barely satisfies the 66-dB specification. However, a 1.55- μm LED was used for the measurement by the vendor, and it is believed that broadband emission tails were the cause of the lower isolation. It is expected that with a laser source this isolation should be greater than 95 dB; 65 dB from the filters and 30 dB from directional coupling. In any case, the units perform their intended function well in the demonstration system. All optical elements of the WDMs are contained inside a small, hermetically sealed plastic housing. The dimensions are given in Appendix C.

3.5 VARIABLE OPTICAL ATTENUATOR

The 104-km demonstration length was accomplished by fusion-splicing of ten fiber segments, each 10.4 km in length. Measurements of the fiber attenuation at both 1.3 μm and 1.55 μm were made on all ten segments prior to splicing. The average attenuation at 1.3 μm was 0.384 dB/km and at 1.55 μm was 0.212 dB/km. Splice loss at 1.55 μm was

measured as each splice was made. The average splice loss was 0.434 dB. Combining the sum of the fiber segment losses and the splice losses gives the total loss of the 104 km of optical fiber as 43.8 dB at 1.3 μm and 26.0 dB at 1.55 μm .

For the next phase of the demonstration, extension of the system link length will be simulated by connecting a single-mode, variable optical attenuator into the transmission path instead of actual fiber. Figure 10 shows the optical system with the attenuator inserted. The attenuator is an optomechanical instrument that produces a calibrated power loss between two optical ports. Light is transmitted via collimated beam optics through a circular, continuously variable neutral-density filter. The filter wheel is directly attached to a front-panel knob which is set to create various attenuation levels. Calibrated dials are imprinted onto the wheel, and the attenuation is read from the dials as the wheel is rotated. Losses are dialed in for each wavelength, and the equivalent length is used as the extended, incremental length beyond 104 km. An average splice loss is chosen and is included every 10 km. For example, to simulate 20 km of fiber at 1.3 μm , using a splice of 0.2 dB, an attenuator loss of 7.88 dB is set. The attenuator exhibits an internal insertion loss offset of typically 4 dB, which is added to all dial settings to get the total attenuation.

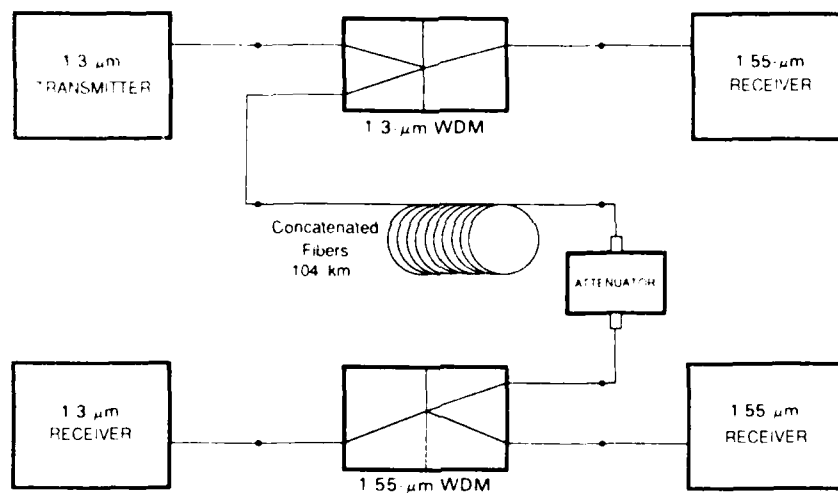


Figure 10. Diagram of optical system with attenuator.

4.0 FOLLOW-ON DEMONSTRATIONS

Follow-on demonstrations will aim for extending the present system length beyond 104 km. The following sections discuss present and projected system lengths and address areas of improvement required to achieve the projected length goals.

4.1 PRESENT 1.3- μm LINK CAPACITY

Currently, the 1.3- μm link limits the maximum distance obtainable. Using present values for laser output power and receiver sensitivity and for fiber, WDM, and splice losses, and allowing a 5-dB safety factor, the present maximum system length is calculated as 120 km. Table 6 summarizes the calculations.

Table 6. Present maximum system length at 1.3 μm .

Average 1.3- μm Laser Output	-0.6 dBm
Average Receiver Sensitivity	-62 dBm
Total Margin	61.4 dB
Less Safety Factor	5 dB
AVAILABLE MARGIN	56.4 dB
Fiber Loss at 1.3 μm	0.415 dB/km
Average Splice Loss	0.43 dB/splice
WDM Loss	1.2 dB (per coupler pair)

Let the maximum segment length be 10 km.

Let the number of segments be N_L ; the total number of splices in the system is $N_L + 3$.

The system loss equation is:

$$56.4 \text{ dB} = (N_L)(0.415 \text{ dB/km})(10 \text{ km}) + (N_L + 3)(0.43 \text{ dB/splice}) + 1.2 \text{ dB (WDM)}$$

Solving for N_L : $N_L = 11.77$

Present maximum length is approximately 120 km.

4.2 AREAS OF IMPROVEMENT FOR 1.3- μm LINK

Several areas of improvement for extending the 1.3- μm link length are addressed. At the end of each paragraph, the amount gained by the improvement, in dB, is given in brackets. N_L is the number of spliced fiber segments, each 10 km in length.

1. Increase laser output power. Currently the average output power of the 1.3- μm laser transmitter is -0.6 dBm (+2.4 dBm peak). As manufacturers become more confident in the reliability of their devices, they will drive them harder, providing higher output powers. Distributed feedback (DFB) lasers show promise of high coupled power also, allowing for possibly +3 dBm average power in the near future [+3 dB gain].

2. Increase receiver sensitivity. Current average sensitivity for the PINFET receiver at 19.2 kbps is -62 dBm. A different receiver design is expected to help considerably. It uses a GaInAs PIN photodiode coupled to an ultralow-noise silicon JFET integrating front-end amplifier to reduce the 1/f noise present in GaAs FETs. This is followed by a differentiator and a 40-kHz low-pass filter. Estimated average sensitivity achievable is -75 dBm [+13 dB gain].

3. Reduce splice losses. Current average splice loss is 0.43 dB. Industry has reported losses of 0.1 dB per splice. A splice loss of 0.1 dB would add about 0.33 ($N_L + 3$) dB to system margin [+0.33 ($N_L + 3$) dB gain].

4. Match source emission wavelength to minimum attenuation wavelength at the 1300-nm window. The present laser transmitter center wavelength was measured at 1.280 μm . Our OTDR operates at 1.3 μm and measured an average attenuation of 0.384 dB/km. Using a wavelength-related error matrix provided by Intelco (References 12, 13, 14), if we measure at 1.3 μm and operate at 1.28 μm , the error is about 0.031 dB/km, or -3.11 dB over 100 km. Thus, while we measure 38.4 dB of fiber loss over 100 km, we are probably experiencing operating losses closer to 41.5 dB. The minimum attenuation wavelength for the dispersion-shifted fiber at the 1.3- μm window is 1.33 μm , as reported by Corning. If a source emission wavelength of 1.33 μm is specified and maintained, an additional reduction in loss of 0.03 dB/km could be achieved [+0.03 dB/km, or +0.3 N_L dB gain].

5. Reduce insertion losses of WDMs. Present losses for the WDMs are 1.2 dB for the 1.3- μm link and 1.3 dB for the 1.55- μm link. By using more efficient WDMs, it is felt that each link could be improved by 0.5 dB at best [+0.5 dB gain].

6. Use fiber with minimum dispersion at the 1300-nm window. Present losses at 1300 nm for the dispersion-shifted fiber averaged 0.384 dB/km. Corning specifies attenuation less than or equal to 0.36 dB/km for their SMF21, 1300-nm fiber. For a length of 100 km, this represents a gain of 2.4 dB. Sumitomo's pure silica-core Z-fiber has an average loss of 0.35 dB/km at 1.31 μm for a gain of 3.4 dB over 100 km. Use of either of these fibers might require employing a DFB laser at 1.55 μm in order to provide adequate bandwidth for the video link [+0.03 dB/km, or +0.3 N_L dB gain].

4.3 PROJECTED 1.3- μm LINK CAPACITY

Implementation of all of the improvements discussed above should render a total effective gain of approximately 17.5 dB plus 0.1 N_L dB. A new projected length for the 1.3- μm link is calculated using the improved values and is summarized in Table 7.

Table 7. Projected system length at 1.3 μm .

Average 1.3- μm Laser Output	+3 dBm
Average Receiver Sensitivity	-75 dBm
Total Margin	78 dB
Less Safety Factor	5 dB
AVAILABLE MARGIN	73 dB
Fiber Loss at 1.3 μm	0.35 dB/km
Average Splice Loss	0.1 dB/splice
WDM Loss	0.7 dB (per coupler pair)

Let the maximum fiber segment lengths be 15 km, and the total segment number be N_L . The total splice number, including WDM splices, is $N_L + 3$. The loss equation is as follows:

$$73 \text{ dB} = (N_L)(0.35 \text{ dB/km})(15 \text{ km}) + (N_L + 3)(0.1 \text{ dB/splice}) + 0.7 \text{ dB (WDM)}$$

Solving for N_L gives $N_L = 13.46$

The total projected length is greater than 200 km.

4.4 PRESENT AND PROJECTED 1.55- μm LINK CAPACITY

Based on present measured values for fiber attenuation and splice losses and information on laser transmitter power, receiver sensitivity, and WDM losses supplied by the manufacturers, a loss budget for the present 1.55- μm link is generated.

Table 8. Present 1.55- μm loss budget.

Average 1.55- μm Laser Output	-3.5 dBm
Average Receiver Sensitivity	-46 dBm
Total Margin	42.5 dB
Less Safety Factor	5 dB
AVAILABLE MARGIN	37.5 dB
Losses:	
Total fiber loss over 104 km	22 dB
Total splice loss	3.9
Additional splice losses at WDMs, lasers and receivers	1.7
WDM losses	1.3
Total losses	28.9 dB
EXCESS MARGIN	8.6 dB

The 8.6-dB excess margin for the present system could be allocated for extending the system length to 135 km. However, losses at 1.3 μm limit the present length to 120 km. This is based on existing values for segment length and component losses at 1.3 μm . Many of the improvements made for the 1.3- μm link will enhance the performance of the 1.55- μm link simultaneously. Additionally, availability of ternary avalanche photodetectors during the latter portion of 1987 should improve the 1.55- μm receiver sensitivity by at least 3 dB.

5.0 CONCLUSIONS

Full-duplex, bidirectional command-control and television data were successfully transmitted over 104 km of unrepeated optical fiber. Commercially available off-the-shelf components were used throughout the system. Injection laser diode transmitters operating at wavelengths of 1.3 and 1.56 μm were employed as the optical sources. InGaAs photodiodes coupled to GaAs FET transimpedance amplifiers were used as the optical detectors. Single-mode, dispersion-shifted optical fiber was the transmission medium. Bulk optic wavelength-division multiplexers isolated the two optical data paths from each other. Television imagery was transmitted using PFM. Control data were Manchester encoded and decoded.

With the present system, the total link length was estimated to be 120 km. Losses at 1.3 μm limit the length. Follow-on demonstrations will improve several areas within the system. Improvements such as increased laser output power, increased receiver sensitivity, reduced fiber splices, and lower fiber attenuation will extend the system length considerably. The projected unrepeated system length, after improvements, is greater than 200 km.

6.0 REFERENCES

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13. "Understanding Errors in Attenuation Testing of Single Mode Fibers," FOTEC Fiber Optic Testing News, Vol. 5, No. 1, Winter 1986, p 4.
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**APPENDIX A:
COMPONENT MANUFACTURER LIST**

Laser Diode Transmitters

PCO, Inc. (PlessCor Optronics)
20200 Sunburst Street, P. O. Box 4809
Chatsworth, CA 91311-6289
(818) 700-1233
POC: Michael Hartman

Model and Price: DTX-15-50 1.55- μ m Transmitter: \$5,950 on 11/5/85
DTX-13-50 1.30- μ m Transmitter: \$4,475 on 11/5/85

General Optronics
Two Olsen Ave.
Edison, NJ 08820
(201) 549-9000

Lasertron, Inc.
37 North Ave.
Burlington, MA 01803
(617) 272-6462

PINFET Receivers

General Optronics
Two Olsen Ave.
Edison, NJ 08820
(201) 549-9000
TWX: 997-9556
POC: Tom DeBerardine

Model and Price: GO PINFET 1.55- μ m Receiver: \$1,220 on 2/5/86
GO PINFET 1.30- μ m Receiver: \$1,020 on 2/5/86

Lasertron, Inc.
37 North Ave.
Burlington, MA 01803
(617) 272-6462

PCO, Inc. (PlessCor Optronics)
20200 Sunburst Street
Chatsworth, CA 91311-6289
(818) 700-1233

Dispersion-Shifted Single-Mode Fiber/Cable

Fiber: Corning Glass Works
Telecommunication Products Department
Corning, NY 14831
(607) 974-4274
POC: John Wahl

Model and Price: SMF/DS 1524: \$0.39 per meter on 4/1/85

Sumitomo Electric U.S.A., Inc.
23440 Hawthorne Blvd., Bldg. 2, Suite 210
Torrance, CA 90505-4762
(213) 373-8493
TWX: 910-344-6368

Furukawa, Mitsui and Co.
1 California Street, Suite 3000
Metal Department
San Francisco, CA 94111
(415) 765-1129

Cable: Siecor Corporation
489 Siecor Park
Hickory, NC 28603-0489
(704) 327-5858 or 5224
POC: Gene Fitzsimmons

Model and Price: 00010F02K010500: \$6.47 per meter on 5/12/86
(This includes the fiber elements)

Wavelength Division Multiplexers

JDS Optics, Inc.
P. O. Box 6706, Station J
Ottawa, Ontario
CANADA K2H 3Z4
(613) 727-1303
Telex 053-4597
POC: Gary Duck, General Manager

Model and Price: WD1315/1.5D 1.3 MUX/1.55 DEMUX: \$800 each WDM on
11/22/85
WD1315/1.3D 1.55 MUX/1.3 DEMUX: \$800 each WDM on
11/22/85

American Photonics, Inc.
71 Commerce Drive
Brookfield Center, CT 06805
(203) 775-8950
Telex 821353

Kaptron, Inc.
3460 W. Bayshore
Palo Alto, CA 94303
(415) 493-8008
Telex 220883

Single-Mode Variable Optical Attenuator

Photodyne, Inc.
1175 Tourmaline Drive
Newbury Park, CA 91320
(818) 889-8770
Telex 181159

Model and Price: 1950XR-010J: \$2,950 on 1/6/87

Intelco Corporation
8 Craig Road
Acton, MA 01720
(617) 264-4485

Anritsu America, Inc.
15 Thorton Road
Oaksland, NJ 07436
(201) 337-1111

Pulse Frequency Modulation Encoder/Decoder

Innovations in Optical Communications, Inc.
9921 Carmel Mountain Road, Suite 242
San Diego, CA 92129
(619) 484-7865

Model and Price: PFM-E/PFM-D: \$3,600 on 1/1/87

APPENDIX B: EQUIPMENT LIST

Portable Fusion Splicer

Power Technology, Inc.
P. O. Box 9769
Little Rock, AR 72219
(501) 568-1995

Model PFS-310

Optical Time Domain Reflectometer (OTDR)

Anritsu America, Inc.
15 Thorton Road
Oakland, NJ 07436
(201) 337-1111

Model MW98A; single-mode plug-ins: MH925A/MH929A

Optical Power Multimeter

Photodyne, Inc.
1175 Tourmaline Drive
Newbury Park, CA 91320
(818) 889-8770
Telex 181159

Model 22XLC with model 585J sensor head

Video Camera

RCA
Fordham Radio
260 Motor Parkway
Hauppauge, NY 11788
(800) 645-9518

Model TC-2011

Video Monitor

Tektronix, Inc.
P. O. Box 500
Beaverton, OR 97077
(503) 627-7111

Model 632

Computer Terminals

Micro-Term, Inc.
512 Rudder Road
St. Louis, MO 63026
(314) 343-6515

Model Mime-2A

Power Supplies

Leader Instruments Corp.
380 Oser Ave.
Hauppauge, NY 11788
(516) 435-8080

Model LPS-152

Lambda Electronics
515 Broad Hollow Road
Melville, NY 11747
(516) 694-4200

Model LL-901-OV, LPT-7202-FM

APPENDIX C: PHYSICAL DIMENSIONS OF COMPONENTS

COMPONENT	DIMENSION		
	Length (in.)	Width (in.)	Height (in.)
PFM Encoder (Housed in Anodized Aluminum Enclosure)	3	3	1-3/4
PFM Decoder (Anodized Enclosure)	6	5	1-3/4
Laser Transmitters (Anodized Enclosure)	4	3-1/2	7/8
Wavelength Division Multiplexers (Plastic Enclosures)	1-3/4	5/16	3/8
PINFET Receiver Circuitry (Anodized Enclosures)	5	3	1-1/2
Manchester Encoder/Decoder	Presently on a 7- by 8-in. Protoboard		

**APPENDIX D:
ELECTRICAL POWER CONSUMPTION OF COMPONENTS**

COMPONENT	CONSUMPTION		
	Voltage (V)	Current (mA)	Power (W)
PFM Encoder	+8	30	2.24
	-8	250	
PFM Decoder	+8	170	3.2
	-8	230	
Manchester Encoder/Decoder	+5	125	0.63
High-Bit-Rate Receiver	+5	50	0.43
	-5	35	
Low-Bit-Rate Receiver	+5	50	0.43
	-5	35	
1.30- μ m Laser Transmitter	-5.2	550	2.9
1.55- μ m Laser Transmitter	-5.2	670	3.5

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